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PHOTOGRAPHY WITH FORTY-INCH REFRACTOR AND TWO-FOOT REFLECTOR

BY
G. W. RITCHEY

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ASTRONOMICAL PHOTOGRAPHY WITH THE FORTY-INCH REFRACTOR AND THE TWO-FOOT REFLECTOR OF THE YERKES OBSERVATORY

BY

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ASTRONOMICAL PHOTOGRAPHY WITH THE FORTY-INCH REFRACTOR AND THE TWO-FOOT REFLECTOR OF THE YERKES OBSERVATORY

G. W. RITCHEY

I. PHOTOGRAPHY WITH THE FORTY-INCH REFRACTOR

IN the original design of the forty-inch refractor of the Yerkes Observatory no provision of any kind was made for direct photography. The objective is a visual one; there is no photographic corrector such as was provided for the great Lick refractor; and there is no powerful auxiliary telescope for guiding, such as are used in the cases of the "standard" photographic telescopes and of the very large photographic refractors at Potsdam and Meudon.

By the use of a method perfected by the writer in 1900, and described in the *Astrophysical Journal* for December of that year, the forty-inch visual refractor was made available for direct photography. The photographic attachment is simple and inexpensive; the entire apparatus cost less than $100. A large number of photographs of star-clusters and of the Moon have been obtained, which are valuable on account of their great scale and fine definition.

The results described in the above-mentioned article were obtained with a small photographic attachment which allowed a field only three inches (about fourteen minutes of arc) square to be photographed at one time. A similar, but larger and more perfect, attachment, taking 8×10-inch plates, has since been constructed from my designs, for use with the great refractor. This allows a field of approximately 36×45 minutes of arc to be photographed at one time, and of course includes the entire disk of the Moon. Many of the photographs described in the present article have been made with the larger apparatus.

The photographic attachment consists of a double-slide plate-carrier for guiding, on which is supported the plate-holder containing a yellow color-screen or ray-filter very nearly in contact with a yellow-sensitive (Cramer instantaneous isochromatic) plate.

The yellow screen freely transmits to the sensitive plate the sharp and intense yellow or visual image produced by the visual objective, and effectually excludes from the plate the blue and other wave-lengths of light which are not included in the visual image, and which would entirely destroy the sharpness of the photographs. Two very fine 8×10-inch yellow screens, one of slightly stronger tint than the other, were obtained after some experimenting. Each screen consists of two thin plates of glass, ground and polished approximately flat; one of these is coated with a film of collodion of a delicate yellow tint. After the collodion film is dry it is flowed with Canada balsam, and the second thin plate, which serves as a cover-glass, is put on. The two plates are bound together with adhesive tape. The screens are brilliantly transparent. When in use one of the screens is placed in the plate-holder directly in front of the yellow-sensitive plate. Screen and plate are separated only by the thickness of the binding tape around the edges of the former.

The double-slide plate-carrier, a device originally suggested by Dr. Common and described by him in *Monthly Notices*, Vol. XLIX, p. 297, permits very perfect guiding or following to be done, without the necessity of an auxiliary or guiding telescope. The large photographic attachment of the forty-inch refractor is illustrated in Plate XII. When in use, the apparatus is connected by four bolts to the large and massive ring, well shown in the illustration, to which all of the various attachments, spectroscopes, etc., with the exception of the micrometer, are in turn connected. This large ring can be racked in and out, and firmly clamped in any position, thus serving for focusing the various attachments. When the four connecting bolts are loosened, the entire attachment can be rotated in position-angle. Such rotation of the double-slide plate-carrier alone can be accomplished by means of the two

smaller rings (one of which can be rotated on the other) which directly support the double-slide. This rotation is convenient, and often necessary, in finding a suitable guiding star. The double-slide arrangement, one slide being at right angles to the other, is shown fairly well in the illustration. The two screws with large milled heads, by which the slides are moved in guiding, are well shown, one to the right of, the other below, the rectangular frame or box which carries the 8×10-inch plate-holder. The plate-holder is not shown.

To the upper side of the rectangular box is connected the small eyepiece by means of which the guiding star at the edge of the field being photographed is watched. A small diagonal prism, which can be seen inside of the rectangular box, overhangs the edge of the photographic plate, receives the light of the guiding star, and reflects it at right angles into the eyepiece. By this arrangement it is almost always possible to use a guiding star whose image is less than four inches distant from the center of the field being photographed. In the eyepiece are two fine cross-lines of spider-web, which are illuminated by faint red light from a very small incandescent lamp, the tubular socket for which is attached to the side of the eyepiece tube. To assist in finding a suitable guiding star, the eyepiece and its accessories are mounted on a slide which can be moved to any desired position on the upper side of the rectangular box, and firmly clamped there. The star which is to be used in guiding is brought to the intersection of the cross-lines in the eyepiece, and is kept there throughout the exposure of the sensitive plate, sometimes lasting four or five hours. The observer sits with his eye at the guiding eyepiece and his fingers on the two screws which move the slides, and thus he introduces any minute corrections of position which he sees are necessary.

The guiding eyepiece gives a magnifying power of about one thousand diameters. It is very seldom, indeed, that a star-image appears quiet in a very large telescope with such a magnifying power as this. Minute irregularities in the movement of the telescope in right ascension are almost always present, and render necessary continual watching and guiding. But larger and more troublesome are the irregular movements of the image which are due to the disturbed condition of the atmosphere. The effects of this lack of tranquillity and homogeneity of the atmosphere are of many kinds. Sometimes the image of the guiding star appears nearly quiet, but is very large and nebulous. At other times the star-image is a small brilliant point, but is dancing about so rapidly that many hundreds of corrections per minute would be necessary in order to follow it. After months of practice with the guiding apparatus the observer is able to introduce between one hundred and two hundred corrections per minute, when necessary. The work becomes almost automatic, but is extremely trying to the eyes when the tremors of the guiding star are rapid. The corrections can be made with great accuracy and almost instantaneously with the double-slide plate-carrier — with an effectiveness incomparably superior to that which can be attained by any other means now known.

The question arises whether the irregular movements of the images of the objects being photographed correspond exactly with those of the image of the guiding star. It would not be difficult to devise an apparatus by means of which the images of two or more stars in different parts of the field could be brought into apparent superposition, and thus this question could be answered. This has not been done, but the sharpness of the photographs obtained when guiding is done with great care is so superior to that resulting from less careful guiding that the conclusion is warranted that when the image of the guiding star is kept at the intersection of the cross-wires, the images of the objects being photographed are kept immovable on the photographic plate.

I have described the double-slide plate-carrier and its use somewhat in detail, because of the very great importance of this apparatus in long-exposure photography, especially with large telescopes. It has been asserted by prominent astronomers that such difficult objects as the dense star-clusters and the planets could never be satisfactorily photographed, because the very powerful telescopes which are necessary to show these objects satisfactorily are so large and heavy that they cannot be moved with the delicacy and quickness necessary to compensate for the constant irregular tremors always visible

with such great telescopes. Experience with the forty-inch refractor, with its enormous weight, the largest instrument thus far successfully used in direct photography, shows that the difficulty is completely solved by the use of the double-slide plate-carrier, in which the mass to be moved in making the necessary corrections is two or three pounds instead of ten or twenty tons. It is safe to assert that for the largest telescopes which could now be constructed, refractors or reflectors, the problem of efficient guiding during long exposures in direct photography is satisfactorily solved.

The photographs of star-clusters and the Moon obtained with the forty-inch refractor and its photographic attachment are certainly not inferior in separation or resolution to those obtained with the largest and best telescopes constructed especially for photography. In the best photographs of star-clusters obtained with the former instrument double stars of 1″ distance are distinctly separated and measurable; and in the best lunar photographs craters one second of arc in diameter (corresponding to a little more than one mile) are shown as distinct rings. These results are due in part to the great size and focal length of the telescope, and in part to the effectiveness of the yellow screen in transmitting to the sensitive plate only those wave-lengths of light for which the color-curve of the objective is very nearly flat.

Even more surprising is the speed of the color-screen method. Although the ratio of focal length to aperture of the telescope is nearly as 19 to 1, fully timed photographs of the Moon are obtained with exposures varying from one-fourth of a second to one second. Stars which are at the visual limit of the instrument (approximately seventeenth magnitude) are photographed with two hours' exposure when atmospheric conditions are good, and with the most rapid yellow-sensitive plates. With five hours' exposure stars fully a magnitude fainter are photographed. This speed is possible, however, only after the observer has become expert in the use of the guiding apparatus, so that he introduces the necessary corrections instantly and almost automatically.

While this speed is greatly inferior to that of a well-made modern reflecting telescope with silvered glass mirrors, it is probable that the forty-inch visual refractor with the color-screen and the best yellow-sensitive plates now obtainable is nearly, if not quite, as rapid in photographing stars and the Moon as a forty-inch photographic refractor (one with its objective corrected for the blue, or so-called photographic, rays) would be. This opinion is based, in part, upon a comparison of photographs obtained with the largest photographic refractors and those obtained with the forty-inch visual instrument. The yellow-screen method utilizes the rays of light which are most freely transmitted by a large objective; it is a well-known fact that while only a small percentage of the yellow rays are lost by transmission through a large and necessarily thick objective, a very large percentage of the blue rays are thus lost; this is undoubtedly the reason why a yellow screen of delicate tint is sufficient to exclude the blue light from the photographic plate when this process is used with the forty-inch refractor.

The color-screen method and the double-slide plate-carrier are of course applicable for photography with all visual refractors, large or small, which are provided with clock-work for driving. By their use fainter stars can readily be photographed with any visual refractor than can be seen directly with the same instrument. In the work with the forty-inch refractor this is particularly noticeable in such cases as those of the fainter stars in the globular star-clusters. Stars which can be detected visually only with difficulty, and with fine atmospheric conditions, appear strong and distinct on the negatives obtained with moderately good atmospheric conditions.

In photographing the Moon at the focus of the forty-inch refractor (without amplification or enlargement of the image) the exposures required are so short that the double-slide plate-carrier is dispensed with, and a simpler apparatus is used to support the plate-holder. This apparatus is so arranged that an exposing shutter mounted in suitable guides can be moved across by hand, in front of the sensitive plate, in making the exposures. Diaphragms with apertures of various shapes, depending upon the phase of the Moon, are attached to the exposing shutter, and serve to equalize

the exposure time, the lunar terminator requiring a much longer exposure than that required for the bright limb. In making the photographs of the Moon, the instant of exposure is not chosen at random. An eye-piece with fine cross-wires is arranged in a tube with a diagonal prism at one end. This tube rests in a V-bearing, so that it can be instantly withdrawn without danger of jarring the telescope. The observer watches the lunar image by means of this eyepiece until an instant occurs when the definition is good and the image appears quiet with reference to the cross-wires; he then instantly withdraws the eyepiece tube (since this would overhang the photographic plate) and at the same time gives the signal to the assistant to move the exposing shutter across. I am indebted to Mr. F. L. Sullivan for able assistance in this and all other direct photographic work with the great refractor.

Plates XIII to XXI, which accompany this article, are from negatives obtained with the forty-inch refractor and its photographic attachment. The photograph of the lunar crater *Theophilus* and its surroundings (Plate XIII) is one of the best of the series, for it was made when atmospheric conditions were exceptionally fine, on the night of October 12, 1900. Much smaller details of the Moon's surface are shown here than have been photographed before. The exposure required in this case was less than one-half of a second. *Theophilus*, with its diameter of sixty-four miles, with its terraced wall or rampart rising three miles in vertical height above the crater-floor, with its great group of central mountains, and the enormous ridges and ravines of its outer slopes, is in many respects the most magnificent example of a lunar crater. The intricate system of radiating ridges of its outer slopes can be traced in the photograph for nearly one hundred miles from the crest of the rampart. Innumerable details are here reproduced with a minuteness and fidelity which are possible only by means of photography.

The illustration of *Mare Serenitatis* and *Mare Tranquilitatis* (Plate XIV) was obtained on the night of August 3, 1901, with an exposure of one second. The enlargement in this case is not nearly great enough to show the finer details visible in the negative, but was decided upon in order to include both plains on one plate. The surfaces of these plains are crossed by numerous ridges or wrinkles, large and small, which are beautifully shown in the original negatives, and on glass positives made from them, but which are difficult to reproduce, on account of the lack of sufficient contrast. The great serpentine ridge in *Mare Serenitatis* and the remarkable system of radiating ridges on *Mare Tranquilitatis* are among the most interesting features of the Moon's surface.

It was a fortunate coincidence, in the case of *Theophilus*, that exceptionally fine atmospheric conditions occurred when the crater was in the best position with reference to the terminator. No opportunity has occurred for photographing *Copernicus* under extremely fine conditions, although on account of the prominence of this superb object such an opportunity has been carefully watched for. The photograph of *Copernicus* shown in Plate XV is from a negative obtained on the night of November 20, 1901, with fairly good atmospheric conditions, and with an exposure of one-half of a second. While *Copernicus* is neither so large nor so deep as *Theophilus*, the system of radiating ridges and deep gullies constituting the outer slopes of the former is probably the most rugged and magnificent to be found on the Moon. The well-known rows of small craters at the west of *Copernicus*, as well as the much smaller rows to the south and northeast of the crater, are well shown in the photograph.

The illustration of *Mare Nubium* and *Bullialdus* (Plate XVI) is from the same large negative as that of *Copernicus*. The photograph shows well the remarkable details of the surface of this great plain—details strikingly different in character from those of *Mare Serenitatis* and *Mare Tranquilitatis*. The region of *Bullialdus* is in such a condition of illumination that it is particularly well seen. In the original negative the details of the outer slopes of *Bullialdus* are shown with remarkable sharpness; some idea of this can be gained from the half-tone illustration.

The photograph of *Clavius* and the surrounding region (Plate XVII) is also from the same negative as that of *Copernicus*. At the time when this photograph was taken the conditions of libration

and of illumination were unusually favorable for this region of the Moon's surface. *Clavius*, with its numerous included craters and other details; *Longomontanus* and *Wilhelm*, in which the details of the ramparts and of the crater-floors are unusually well shown; the extremely rough country north of *Wilhelm;* and the "metropolitan" crater *Tycho* conspicuous for its enormous depth, are among the most remarkable objects of this region.

The photograph of the great system of bright rays about *Tycho* (Plate XVIII) is from a negative obtained March 31, 1901. While the negative is not so extremely sharp as some others, a much greater enlargement than was possible here would be necessary to show well the astonishing richness of detail in this system of bright rays which is present in the original negative. The exposure time in this case was one-fourth of a second.

The half-tone process of reproduction is especially disappointing in the case of the star-clusters. Not only are hundreds of the fainter stars entirely lost, but the groups of bright stars which are sharply separated in the original negatives appear only as white patches in the half-tone illustrations. The writer expects to include, with the copies of this paper which are sent to observatories and individuals especially interested in astronomical photography, large prints, on photographic paper, of the subjects which have suffered most in reproduction by the half-tone process. The expense of these photographic prints has been met by a generous friend who is interested in the work.

The illustration of the Great Cluster in *Hercules*, *Messier* 13 (Plate XIX), is from a negative obtained on the night of April 25, 1901, with the large photographic attachment and with an exposure of three hours. In the original negative the center of the cluster is well resolved. Lines and groups of stars of between the sixteenth and seventeenth magnitudes, and with distances down to 1′, are well shown and distinctly separated. More than three thousand stars are shown on the negative, many of which are so faint that they are beyond the visual limit of the great telescope.

Smaller, but richer and more condensed, than *Messier* 13 is that superb cluster *Messier* 15 *Pegasi* (Plate XX), although the effect of richness and condensation is to a large extent lost in the illustration, on account of the great scale and the loss of the fainter stars. The sharpest negative of this object was obtained on the night of October 3, 1900, with an exposure of three hours. On account of exceptionally fine atmospheric conditions during nearly one hour of this exposure, this is one of the best of the star-cluster photographs. A comparison of this photograph with others of the same object which have been published will demonstrate the advantages of telescopes of great focal length, and of an efficient guiding mechanism, in the photography of these difficult objects.

Two or more very sharp negatives of each of the dense globular clusters *Messier* 2 *Aquarii*, *Messier* 3 *Canum Venaticorum*, and *Messier* 5 *Librae*, as well as of some of the larger and more open clusters, have also been obtained. It is believed that on account of the great scale and excellent definition of these photographs they will prove extremely valuable for comparison with photographs obtained several years later, in the search for change and rotation in these clusters.

The photograph of the central parts of the great nebula in *Orion* (Plate XXI) was obtained with the forty-inch refractor with an exposure of three hours, January 20, 1901. The night was extremely transparent, but atmospheric conditions were not fine in other respects, so that the star-images appear large. The yellow-screen process is not well adapted for the photography of nebulæ, since the light of these objects consists almost exclusively of green and blue rays. The blue rays are entirely excluded by the yellow screen, and the green rays, which are imperfectly transmitted (and by which the nebula is photographed) are not brought to a focus in the same plane in which the star-images are in best focus. But similar difficulties in regard to focus are encountered even with the best photographic refractors.

It is only with the reflecting telescope that the intolerable difficulties due to imperfect achromatism are entirely absent. In the present case the focal setting used was that which is best for the stars; consequently the details of the nebula are slightly out of focus. The photograph is introduced

in order to call attention to the difficulties just described, and also because, on account of the great scale, the details of the central parts of this celebrated nebula are shown better than in any other photographs of this object with which the writer is acquainted.

II. PHOTOGRAPHY WITH THE TWO-FOOT REFLECTOR

The two-foot reflector of this observatory (Plate XXII) was described somewhat at length in my article in the *Astrophysical Journal* for November, 1901; a detailed description of the instrument is therefore not necessary here; the following statements may, however, be made in regard to it:

The large mirror has a clear aperture of $23\frac{1}{2}$ inches and a focal length of 93 inches. The instrument is used as a Newtonian for direct photography, and also as a Cassegrain for direct photography and spectroscopic work; the convex Cassegrain mirror is 5 inches in diameter and gives an equivalent focal length of 38 feet; as there is no central hole through the large mirror, three reflections are necessary when the convex mirror is used. The mounting is massive and rigid. The tube consists of a skeleton framework of steel tubes and cast-aluminum rings. The driving-clock and clock-connections are unusually large and strong. A small double-slide plate-carrier which allows a field three inches square to be photographed, is used for guiding in direct photography at either the primary or secondary focus. All of the mechanical parts of the instrument were made in the instrument shop of the observatory; the optical parts were made by the writer.

Special attention was given to the perfection of the optical parts; to the stability of the mirror supports and the rigidity of the skeleton tube, in order that the adjustment or collimation of the optical parts might remain perfect during long exposures; and to the refinement of the driving mechanism and the guiding apparatus. In nearly all respects the same degree of care and refinement was used in the making of this instrument as is given in the case of the best modern refractors.

The performance of the instrument in direct photography at the primary focus is highly satisfactory. As stated in my previous article, "the combination of (1) stability of position of the mirrors, (2) rigidity of skeleton tube, (3) smoothness of clock-driving, and (4) accuracy of guiding made possible by the use of the double-slide plate-carrier, is so effective that when atmospheric conditions are good the image of a guiding star in the eyepiece does not wander so much as one one-hundreth of a millimeter during an exposure of three or four hours. The accuracy with which the star-images are kept immovable on the photographic plate is nearly as great, as is shown by the photographs. In the best negative with four hours' exposure the images of the smaller stars near the center of the field are about $2''$ in diameter. Double stars of $2''.5$ distance are sharply separated, and those of $2''$ distance, corresponding to about 0.02 mm. on the photographic plate, are measurable."

"No greater mistake could be made than to suppose that the finest atmospheric conditions are unnecessary to secure the best results in photographing the nebulæ. With such conditions the photographs show that these objects are not diffused hazy masses, but that their structure is generally most complicated, often consisting of exquisitely fine filaments and delicate narrow rifts. In these photographs the intersections of such filaments and rifts can be set upon, in the measuring machine, with almost the same degree of accuracy that is possible in the case of star-images. Changes of form in the nebulæ, if such occur, could be detected with certainty by means of such photographs."

A large refracting telescope, whether visual or photographic, is not an efficient and economical instrument for photography, either direct or with the spectroscope, when compared with a modern reflector. The two-foot reflector, with its focal length of ninety-three inches and with its aperture reduced to fifteen inches, photographs seventeenth-magnitude stars with two hours' exposure. This speed is equal to that of the forty-inch refractor with the color-screen, with the finest atmospheric conditions, *i. e.*, when the guiding star appears in the eyepiece as an extremely small point, and when irregular movements of the guiding star are so slow and so small that they can be readily followed. It is probable that this speed is nearly, if not quite, equal to that of the largest photographic refrac-

tors in use. When the full aperture is used, the two-foot reflector photographs seventeenth-magnitude stars with forty minutes' exposure.

That the great difference in speed between refractors and reflectors in photographing stars is not due largely to difference of angular aperture is amply proved by the few results which have been obtained with the two-foot reflector when used as a Cassegrain, *i. e.*, with the addition of the convex mirror, which gives an equivalent focal length of thirty-eight feet. Photographs made for comparison *when atmospheric conditions are good* (so that star-images appear as very small points even at the secondary focus), show that with this great equivalent focal length stars are photographed very nearly as rapidly as at the primary focus; the difference in speed is so slight that it is readily accounted for by the assumption that about 10 per cent. of the light is lost by the additional reflection at the convex mirror. I am aware that this result is apparently at variance with theories in regard to the effect of focal length (when the aperture remains constant) upon the size and intensity of the diffraction disks of star-images, and consequently upon the speed with which such images are photographed.

The great superiority of the reflecting telescope in photography is unquestionably due, primarily, to its perfect achromatism. The importance of this has of course been recognized for many years, but I think that the *degree* of the importance, *in photography*, of perfect achromatism has not been appreciated — that the effect of this achromatism in giving great speed as well as great sharpness has not been fully recognized. Hardly less important is the fact that in the case of large instruments much less light is lost, of the wave-lengths which are most effective in photography, by absorption at the silver surfaces of a reflector than by absorption and reflection in an objective.

In the case of the refractor the difficulties due to imperfect achromatism, as well as the percentage of light lost in transmission, increase rapidly with increase of size of the objective. In the case of the reflector, however, a large instrument is as perfectly achromatic as a small one, and the percentage of light lost does not increase with increase of aperture. But the reflecting telescope has not been developed to the state of refinement which has been attained in the case of the refractor. This is probably due, to a large extent, to the fact that the difficulties and peculiarities of the reflector have not been thoroughly understood; at any rate, it is certain that these difficulties have not, in the past, been successfully met. It is almost superfluous to state that the great reflectors of the past, without exception, have been in many respects extremely crude instruments; in all cases without the great rigidity and stability of construction which are absolutely essential to the successful performance of a reflector; and in all cases without the refinement of workmanship, in both optical and mechanical parts, which are attained in the great modern refractors. In saying this I certainly intend no criticism of the able and skilful men who have been the pioneers in the development of the reflecting telescope, and who have contributed so much to both the methods and the results of astronomical observation.

It is safe to assert that the peculiar difficulties of the reflecting telescope are now thoroughly understood, and that all difficulties which relate to its mechanical and optical construction have been successfully solved.

As a result of the improvements and developments in glass-making, in optical work, and in the methods and materials of modern mechanical construction; and as a result, no less, of the experience of those who have both made reflecting telescopes of moderate size and used them successfully in astronomical photography, there can be no doubt whatever that a great reflecting telescope of five or eight feet aperture could now be constructed with all of the refinement of the two-foot reflector or the forty-inch refractor.

The speed of the reflector in the photography of nebulæ is of course due largely to its great angular aperture. All of the reflector photographs which accompany this article, with the exception of that of *Messier* 51, were made with the aperture of the 23½-inch mirror reduced to 18 inches, in order that good definition might be secured over a larger field than is well covered when the full aperture is used. The ratio of focal length to aperture was therefore as 5⅙ to 1. These photographs

show what can be done with a reflecting telescope of very moderate size (aperture 18 inches, focal length 93 inches) when sufficient care is given to the perfection of the mirrors and mounting, and when an effective method of guiding is employed.

The photograph of the great nebula in *Orion* (Plate XXIII) was obtained with an exposure of one hour. Even with this short exposure faint extensions of the nebula and a great amount of delicate structure in the moderately bright parts are shown, which cannot be detected visually with either the two-foot reflector or the 40-inch refractor. A comparison of this photograph with that of the central part of the same nebula obtained with the forty-inch refractor (Plate XXI), and also with other published photographs of this object obtained with photographic refractors, gives some idea of the great efficiency of a well-made modern reflector of large angular aperture in such work.

The photograph of the great nebula in *Andromeda* (Plate XXIV) was obtained with an exposure of four hours, although one hour's exposure, or less, is sufficient to show the general characteristics of the object well. This is one of the most magnificent examples of a spiral nebula to be found in the heavens, yet its spiral character was never suspected from visual observations. In the original negative the spiral structure is visible almost to the center of the nebula, and the stellar nucleus is distinctly seen. Sharply defined narrow rifts and dark holes near the center are shown on all of the negatives of this object; no trace of these can be detected visually with any telescope.

The photograph of the spiral nebula *Messier* 33 *Trianguli* (Plate XXV) was obtained with an exposure of four hours. This nebula is very large and very faint; the spiral character of its central parts was discovered by Lord Rosse; by far the greater part of the complicated structure shown in the photograph is too faint to be detected visually. While differing greatly in general appearance from the great *Andromeda* nebula, *Messier* 33 resembles the latter in several striking characteristics; in the presence of dark rifts and holes in and near the bright central parts, and in the tendency of its outer branches to break up into stars. The central parts of this object appear decidedly nebulous; the outer parts consist of very faint nebulosity and of numerous curved streams or wisps of nebulous stars; hundreds of these star-like condensations are so distinctly shown on the original negative that they may be well seen even in the half-tone reproduction. There can be no doubt of the physical connection between the nebulosity and the streams of minute stars; this object therefore affords what is apparently a most striking example of a spiral nebula condensing into stars.

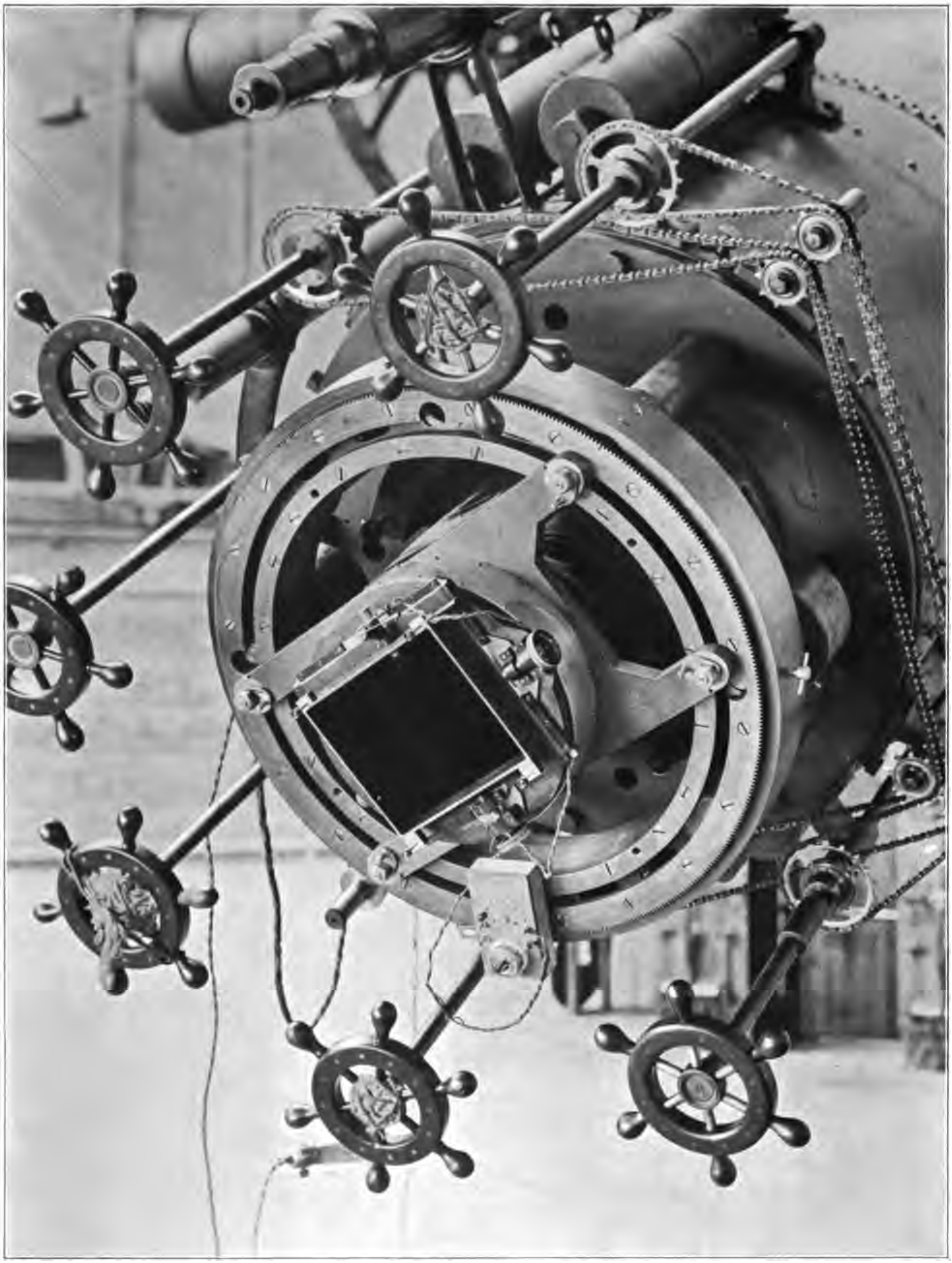
The illustration of the nebulosities in the *Pleiades* (Plate XXVI) is from a negative obtained with an exposure of three and one-half hours. This photograph is extremely difficult to reproduce properly, on account of the great difference in brightness between the bright stars and the faint masses of nebulosity. Some idea of the intricate filamentous structure of these masses may be gained from the half-tone plate. In the original negative, from which I hope a more satisfactory reproduction may yet be secured, the entire field, nearly two degrees square, is covered with a network of filaments, of which those in the southwest part of the photograph, and apparently connected with the great curved mass of streamers about *Merope*, are the most conspicuous. Only the brighter filaments of this vast network are shown in the reproduction.

The photograph of the nebula *N. G. C.* 6960 (Plate XXVII) was obtained with an exposure of four hours, and that of *N. G. C.* 6992 (Plate XXVIII) with an exposure of three hours. These nebulæ are the most remarkable examples of filamentous nebulæ which I have photographed. They lie near together in the Milky Way in the constellation of *Cygnus;* they are apparently only the brightest parts of one great nebula, as extremely faint nebulous masses can be seen in the negatives, extending from one to the other. The nebula *N. G. C.* 6960 apparently lies exactly on the boundary between the dense region of stars to the east (the right-hand side in the illustration) and the region to the west which is comparatively void of stars. Instances of this kind occur again and again, and strongly suggest some intimate physical connection between such nebulæ and the dense masses of stars in their neighborhood. These photographs afford striking illustrations of the wonderful richness and complexity of structure

of the nebulæ, and of the importance of photography in the study of these very faint objects. When it is remembered that these photographs, showing such delicacy of detail, are obtained with a reflecting telescope of only eighteen inches aperture and ninety-three inches focal length, we can gain some idea of the results which might be obtained in the photographic study of the nebulæ with a thoroughly well-made reflecting telescope which would be comparable in size, cost, and refinement of workmanship with the great modern refractors.

The photograph of *Messier* 51 (Plate XXIX) was obtained with an exposure of six hours and with an aperture of 22 inches. With this long exposure and large angular aperture a very intense negative was obtained, which shows much exterior nebulosity; the latter is so faint, however, that it is almost entirely lost in the half-tone reproduction. Perhaps the most remarkable part of the very faint outer nebulosity is a great curved mass which forms a continuation of the conspicuous branch of the nebula to the extreme south; this continues toward the east, curves toward the north, and then toward the northwest, and joins the parts of the nebula to the north. The reproduction shows well the details of the two bright main branches of the spiral, and also the faint wisps and filaments between them; the latter are far beyond the reach of all telescopes visually. The faintest stars shown on the original negative are about two magnitudes fainter than those which are at the visual limit of the forty-inch refractor.

I am indebted to Mr. F. G. Pease for able assistance in securing the reflector photographs, and in preparing all of the photographic enlargements for the engraver's use. Great credit is due to the Binner-Wells Co., engravers, for the unusual care and skill with which the photographs have been reproduced.



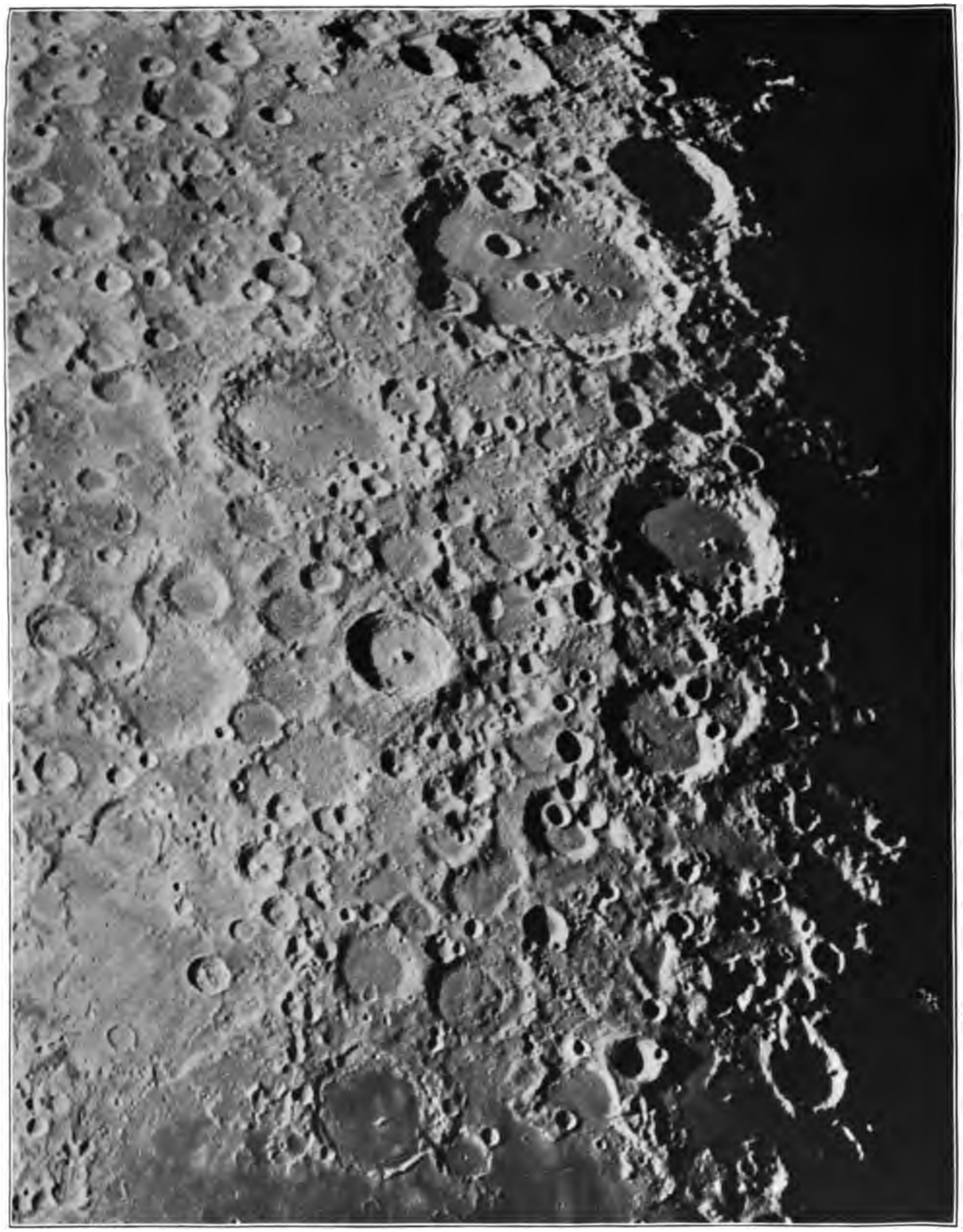
LARGE DOUBLE-SLIDE PLATE-CARRIER ATTACHED TO FORTY-INCH REFRACTOR

LUNAR CRATER *COPERNICUS* AND SURROUNDINGS

SCALE: 1.02 Meters to Moon's Diameter

MARE NUBIUM, BULLIALDUS, ETC.

SCALE: 0.79 Meter to Moon's Diameter

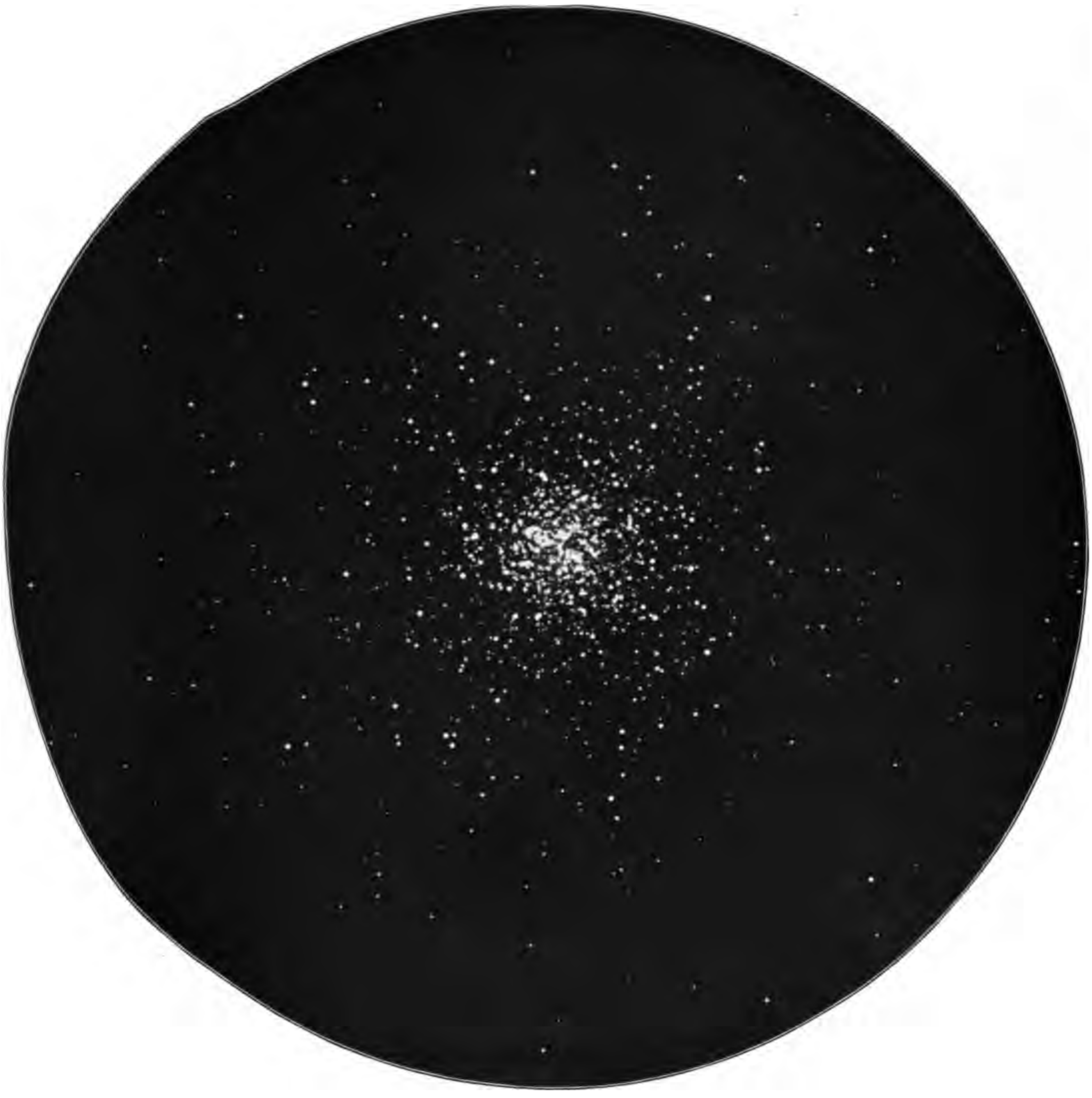


LUNAR CRATERS *CLAVIUS, LONGOMONTANUS, TYCHO*, ETC.

SCALE: 0.79 Meter to Moon's Diameter

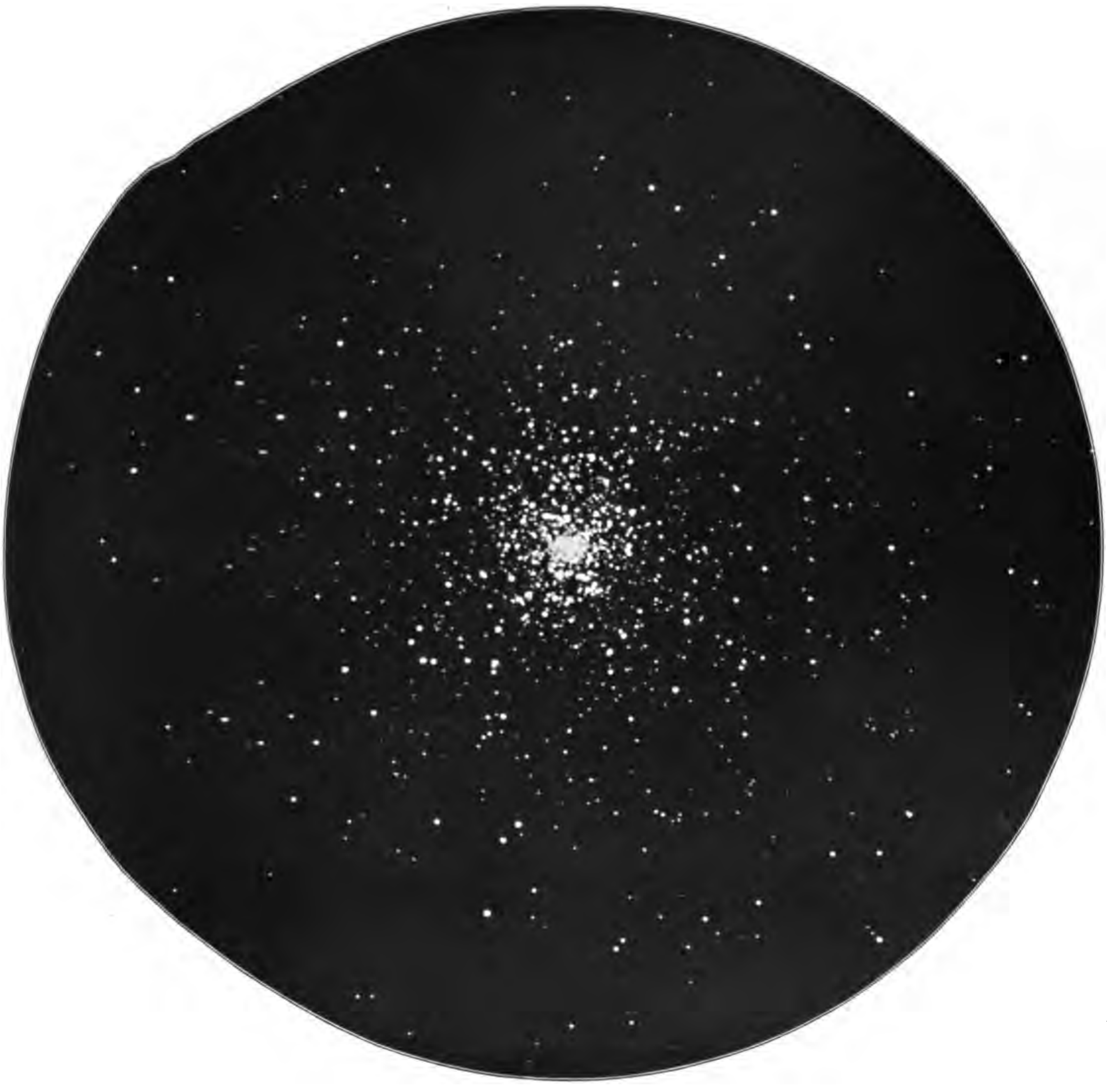
SYSTEM OF BRIGHT RAYS ABOUT *TYCHO*

SCALE: 0.33 Meter to Moon's Diameter



STAR-CLUSTER *MESSIER* 13 *HERCULIS*

SCALE: $1^{mm} = 4.'66$

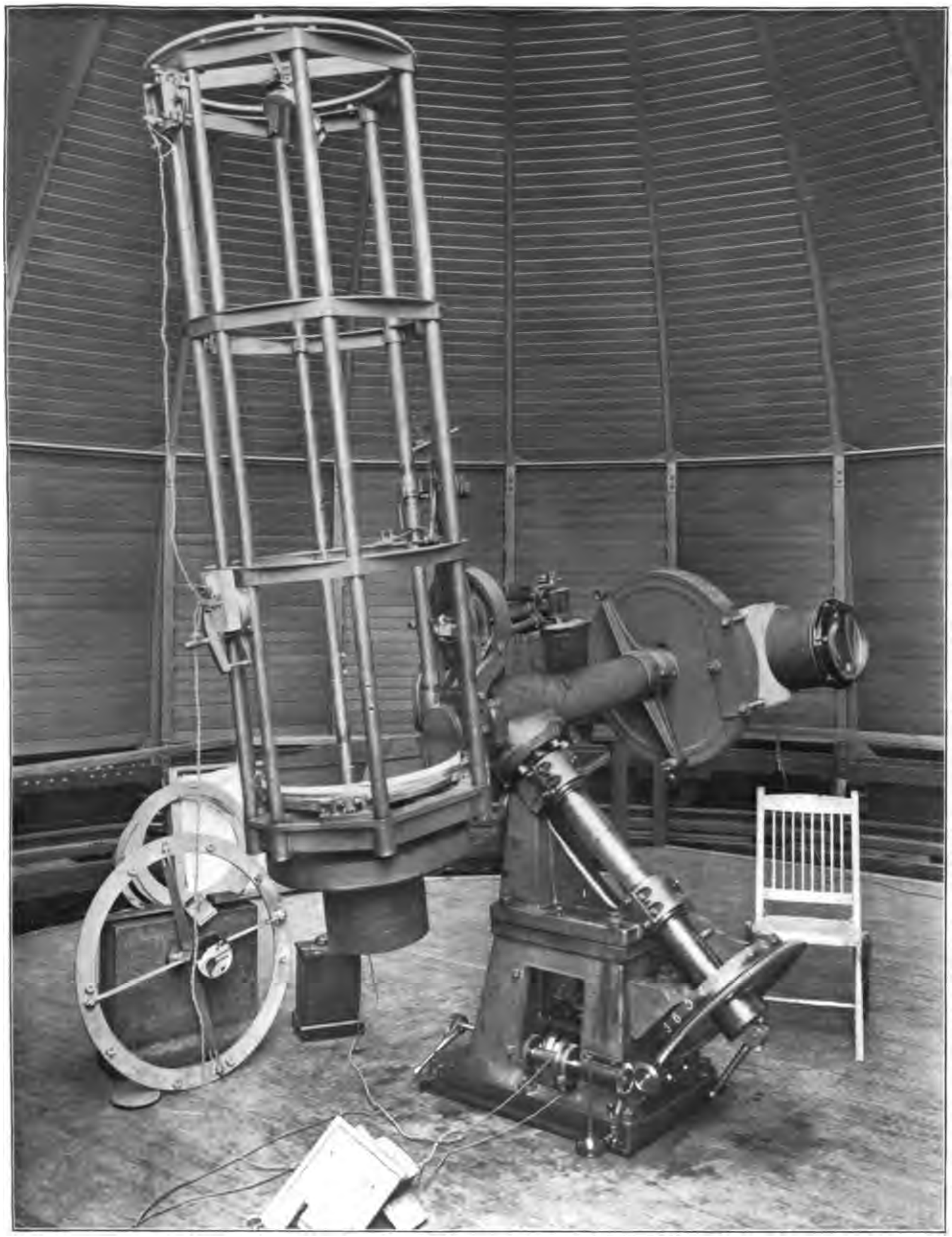


STAR-CLUSTER *MESSIER* 15 *PEGASI*

SCALE: 1mm=3.′22

Central Part of Great Nebula in *Orion*

Scale: 1mm = 4″



Two-Foot Reflecting Telescope of the Yerkes Observatory

GREAT NEBULA IN *ORION*

SCALE: $1^{mm} = 20''$

October 19, 1901

Great Nebula in Andromeda

Scale: 1mm = 27″.5

September 18, 1901

SPIRAL NEBULA *MESSIER* 33 *TRIANGULI*

SCALE: $1^{mm} = 15\rlap{.}''5$ September 4 and 6, 1902

NEBULOSITY IN THE *PLEIADES*

SCALE: $1^{mm} = 21''$

October 19, 1901

NEBULA IN *CYGNUS*, *N.G.C.* 6960

SCALE: $1^{mm} = 18''.3$ August 1, 1902

NEBULA IN *CYGNUS*, *N.G.C.* 6992

October 5, 1901

SCALE: $1^{mm} = 20''.3$

SPIRAL NEBULA *MESSIER* 51 *CANUM VENATICORUM*

SCALE: 1mm = 13.″2

June 3, 1902